Red Clump Stars as a Tracer of Microlensing Optical Depth

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ABSTRACT

Zaritsky and Lin have recently suggested that the color magnitude diagram of the Large Magellanic Cloud (LMC) contains evidence of foreground red clump stars. They interpret this as evidence of tidal debris or a dwarf galaxy at a distance of ~ 35 kpc which may be responsible for the large gravitational microlensing optical depth observed by the MACHO Collaboration. I derive a relationship between the microlensing optical depth of such a foreground population and the observed density of foreground red clump stars. Recent observational determinations for Pop I and Pop II stellar mass functions are used to show that the surface density of foreground red clump stars claimed by Zaritsky and Lin implies a microlensing optical depth in the range $\tau_{fg} = 0.8 - 3.6 \times 10^{-8}$ which is only 3-13% of τ_{LMC} as determined by the MACHO Collaboration. If the foreground population has a similar star formation history to the LMC, then the implied τ_{fg} is only 3-4% of τ_{LMC}.

Subject headings: dark matter - gravitational lensing

1. Introduction

The MACHO Collaboration has recently reported a microlensing optical depth of $\tau_{LMC} = 2.9^{+1.4}_{-0.9} \times 10^{-7}$ toward the Large Magellanic Cloud (LMC) (Alcock et al. 1997a). This is a substantial fraction of the microlensing optical depth predicted by a standard Galactic model with a dark halo composed entirely of massive compact objects (Machos), and it suggests that at least a partial solution to the dark matter problem has been found. However, the timescales of the detected microlensing events seem to indicate a typical lens mass of $\sim 0.5 M_\odot$ which is in the mass range of normal main sequence stars. Main sequence stars are too bright to comprise a significant amount of the Galaxy's dark halo, so if the lensing objects are indeed composed of baryons, they must be in another form. White dwarfs are an obvious possibility. Since white dwarfs generally form as remnants of luminous stars, however, there are a number of observational constraints on white dwarf halo models (Adams & Laughlin 1996; Chabrier & Segretain 1996; Fields, Mathews, & Schramm 1997; Gibson & Mould 1997). Another possibility is that the lensing objects are not made up of baryons but are black holes which formed at the QCD phase transition (Jedamzik 1997).

It is also possible that the microlensing events detected by the MACHO collaboration do not represent a large contribution to the total mass of the Galactic halo. Zhao (1996) has suggested that there might be a previously unknown dwarf galaxy which, by chance, happens to lie in the foreground of the LMC. It is *a priori* rather unlikely for such a dwarf galaxy to be positioned in front of the LMC, but this is still a possibility. Zhao (1997) has also suggested that the foreground object might be the debris of a dwarf galaxy that is in the process of being tidally disrupted or perhaps even a tidal tail of the LMC itself.

Zaritsky & Lin (1997) have recently suggested that there may be evidence of such a foreground population visible in color magnitude diagrams of stars seen in the direction of the LMC. They find a feature on the giant branch of the LMC color magnitude diagram which they interpret as a population of red clump stars in the foreground of the LMC at a distance of ~ 35 kpc. They suggest that this population may be associated with a dwarf galaxy or tidal tail that is massive enough to explain the large microlensing optical depth observed by the MACHO Collaboration.

In this *Letter*, I address the implications of Zaritsky & Lin's interpretation of their observations directly by deriving a relation between the observed density of red clump stars and the microlensing optical depth of a normal stellar population that the red clump stars belong to. The normal stellar population is assumed to have an initial mass function (IMF) similar to the observed mass function in the Galactic disk or in globular clusters. It is then shown that the surface density of foreground red clump stars implied by Zaritsky & Lin yields a microlensing optical depth much smaller than the value observed by the MACHO Collaboration.

2. Optical Depth of a Foreground Population

Let us assume that the foreground stellar population has a Salpeter-like initial mass function: $n(m) \propto m^{-2.3}$ for $m_1 < m < m_2$. Here and throughout this paper lower case m will always refer to a mass in units of $M_\odot$. For $m < m_1$, $n(m)$ is assumed to be constant, and stars with $m > m_2 = 10$ are ignored. This form of the IMF can be used with $m_1 = 0.6$ to represent a stellar population similar to the Galactic disk (Pop I) (Gould, Bahcall, & Flynn 1997) and with $m_1 = 0.3$ to represent an older globular cluster type IMF (Pop II) (De Marchi & Paresce 1997). For simplicity, the stellar population is described by a single turn-off mass, $M_{to} = m_{to}M_\odot$, and a main-sequence lifetime $t_{ms} = 1.1 \times 10^{10}m_{to}^{-3.75}$ yrs which is appropriate for stars with $M \sim M_\odot$ (Mihalas & Binney 1981). (The value quoted for t_{ms} is actually the pre-horizontal branch lifetime.) We will also need the lifetime of the stars in the red clump. This we take to be $t_{RC} = 10^8$ yrs independent of the star's initial mass (Castellani, Chieffi, & Pulone 1991). Finally, we must consider the fate of the stars which have evolved past the horizontal branch. These are assumed to have become white dwarfs with a mass given by $M_{wd} = 0.15M + 0.38M_\odot$ (Iben & Renzini 1983).

With these assumptions it is straight forward to work out the expected microlensing optical depth for a foreground stellar population with a measured surface density of red clump stars. The total mass in stars is given by

$$
\begin{aligned}
\mathcal{M} =& A\left[\int_0^{m_1} m_1^{-1.3}dm + \int_{m_1}^{m_{to}} m^{-1.3}dm + \int_{m_{to}}^{m_2} m^{-2.3}m_{wd}dm\right] \\
=& A\left[4.333m_1^{-0.3} - 0.2653 - 2.833m_{to}^{-0.3} + 0.2923m_{to}^{-1.3}\right] \;,
\end{aligned}
\tag{1}
$$

where A is an arbitrary normalization constant. In order to determine the total number of red clump stars we must determine the interval in initial mass that the red clump progenitor span. This is just the interval m to $m(1 + \delta)$ where $\delta = t_{RC}/(3.75t_{ms})$ since $t_{ms} \propto m^{-3.75}$. Thus, the total number of red clump stars is given by

$$
\begin{aligned}
N_{RC} =& A\int_{m_{to}}^{(1+\delta)m_{to}} m^{-2.3}dm \\
=& A\,m_{to}^{-1.3}\delta = 0.00242\,A\,m_{to}^{2.45} \;.
\end{aligned}
\tag{2}
$$

Equations (1) and (2) give the total stellar mass per red clump star:

$$
\frac{\mathcal{M}}{N_{RC}} = m_{to}^{-2.45}\left(1788m_1^{-0.3} - 110 - 1169m_{to}^{-0.3} + 121m_{to}^{-1.3}\right) \;.
\tag{3}
$$

Now, the microlensing optical depth of a foreground population is just the fraction of the sky covered by the Einstein rings of all the lenses. The linear size of the Einstein ring radius is given by $R_E = 2\sqrt{GMx(1 - x)L}$ for a lens of mass M at a distance of xL for source stars at a distance L. Thus, the microlensing optical depth of a foreground population with an angular surface density of $1M_\odot$ per square degree is just

$$
\tau_1 = \frac{1 - x}{x}3.95 \times 10^{-14} \;,
\tag{4}
$$

where we have assumed source stars in the LMC at 50 kpc. Equations (3) and (4) can be combined to yield an expression for the microlensing optical depth of a foreground population of stars with σ_{RC} red clump stars per square degree:

$$\tau_{fg} = 3.95 \times 10^{-14} \frac{1-x}{x} \frac{\sigma_{RC}}{m_{to}^{2.45}} \left(1788 m_1^{-0.3} - 110 - 1169 m_{to}^{-0.3} + 121 m_{to}^{-1.3}\right) \ . \tag{5}$$

A couple of trends are apparent from equation (5). First, a Pop I initial mass function ($m_1 = 0.6$) implies a higher microlensing optical depth than a Pop II IMF ($m_1 = 0.3$) for a fixed turn-off mass. This is because the Pop II IMF has more low mass stars per red clump star. Also, for a fixed IMF, an old population with a lower turn-off mass will have a higher microlensing optical depth per red clump star. This is because older stars spend a smaller fraction of their lifetime as red clump stars.

3. Application to Zaritsky & Lin's Observations

Equation (5) can now be used to estimate the microlensing optical depth of the population of foreground stars that Zaritsky & Lin (1997) have inferred from their LMC color magnitude diagram. They have identified a feature in their color magnitude diagram which they interpret as a red clump population in the foreground of the LMC at a distance of $\approx 35\,\mathrm{kpc}$, but other interpretations of these observations are certainly possible. It could be that this feature on the LMC giant branch is caused by stellar evolution, for example. For the purpose of this paper, however, we will assume that Zaritsky & Lin's interpretation of their observations is correct. The "foreground" clump population is estimated to have a surface density of $\lesssim 5$ to 7% of the surface density of LMC red clump stars in the fields that they observed. They found approximately 70,000 stars in the red clump and the giant branches in the three square degrees of their survey which implies that the foreground population should have approximately $\sigma_{RC} = 1200$ red clump stars per square degree. Inserting this value and $x = 0.7$ (for a population at 35 kpc) into equation (5) yields the results shown in Figure 1. This figure shows the estimated optical depth as a function of the main sequence turn-off mass for both Pop I ($m_1 = 0.6$) and Pop II ($m_1 = 0.3$) initial mass functions. The models for stellar populations in the foreground of the LMC which seem the most plausible hold that the foreground object is composed of tidal debris from either LMC-Milky Way interactions or LMC-SMC interactions (Zhao 1997; Zaritsky & Lin 1997). These models would suggest that the foreground population is relatively young, like the LMC. Thus, $m_{to} = 1.5$ and $m_1 = 0.6$ are probably appropriate for such a population. Inserting these numbers in equation (5) yields a foreground microlensing optical depth of $\tau_{fg} = 7.6 \times 10^{-9}$ which is 2.6% of τ_{LMC} as observed by MACHO. Thus, it is unlikely that tidal debris in the foreground of the LMC can explain a significant amount of the observed microlensing optical depth.

A larger microlensing optical depth can be obtained if we consider the extreme, old Pop II case with $m_{to} = 0.9$ and $m_1 = 0.3$. This yields a foreground microlensing optical depth of $\tau_{fg} = 3.6 \times 10^{-8}$, but this is still only 13% of the observed value. Furthermore, an old population
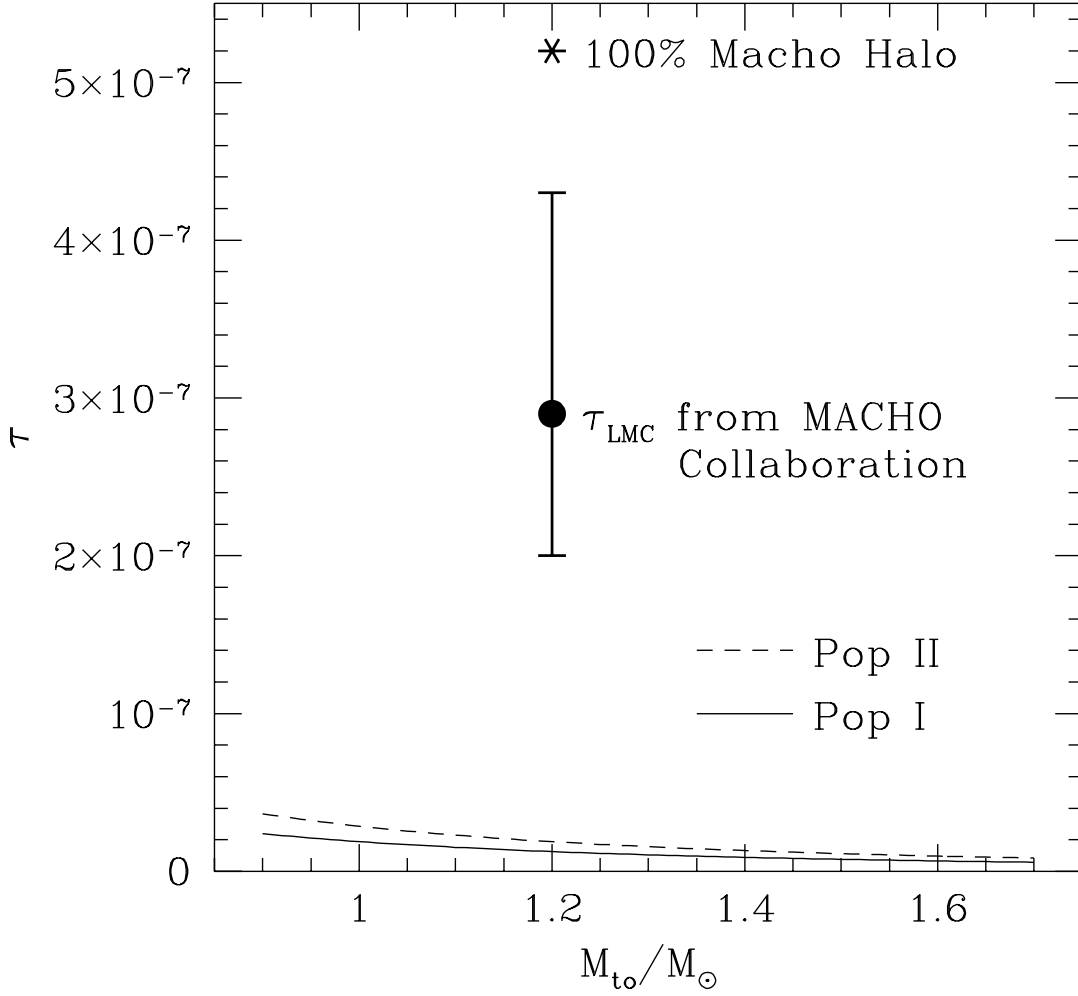
Fig. 1.— The microlensing optical depth of a population of stars with a angular density of $\sigma_{RC} = 1200$ red clump stars per square degree located at 35 kpc in the foreground of the LMC is plotted as a function of the main sequence turn-off mass, M_{to}. The solid line assumes a Pop I initial mass function and the dashed line assumes a Pop II initial mass function. For comparison, the microlensing optical depth, τ_{LMC}, measured by the MACHO Collaboration and the predicted optical depth for a standard halo composed entirely of Machos are also shown. (Strictly speaking, τ_{LMC} is a lower limit on the microlensing optical depth because MACHO is only sensitive to microlensing events with Eintein diameter crossing times between 2 and 200 days.)

should have a large number of RR Lyrae stars which could be seen in the foreground of the LMC. Such foreground RR Lyrae are not seen in the MACHO database (Alcock et al. 1997b) although the search of the MACHO database was limited to RR Lyrae brighter than $V = 18$ which means that they are only sensitive relatively bright RR Lyrae at 35 kpc.

4.   Discussion and Conclusions

Using initial mass functions determined from recent HST observations of globular clusters and the Galactic disk, I have derived a relationship between the surface density of red clump stars and the microlensing optical depth of the parent stellar population. This relationship has been used to show that the foreground population suggested by Zaritsky & Lin does not have a mass in stars to explain the microlensing optical depth observed toward the LMC by the MACHO Collaboration.

A number of other authors have also estimated the microlensing optical depth for such a foreground stellar population. Zaritsky & Lin estimated $\tau_{fg} = 1.2 \times 10^{-7}$ which is 40% of τ_{LMC} as measured by the MACHO Collaboration and 3-16 times the estimates derived here. Their estimate is based upon an estimate of the surface density of the LMC disk which assumes that all of the mass of the central 3 kpc of the LMC is made up of stars in the disk. Gould (1997) points out that this is an unreasonable assumption for the LMC, and he notes that Zaritsky & Lin made an error when correcting the apparent LMC surface density for inclination. Zaritsky & Lin also use the spherical formula to estimate the mass of the LMC disk (which is not very spherical) and make no correction for the fact that their field is a low density "inter-arm" region of the LMC disk (Freeman, private communication). Each of these errors has an effect at about the factor of 2 level, but all of them tend to make Zaritsky & Lin's τ_{fg} estimate too large. The combination of these errors can easily explain the factor of 3-16 discrepancy with the results presented here.

Gould (1997) and Johnston (1997) have also considered the microlensing optical depth of a foreground object like that proposed by Zaritsky & Lin. Gould has pointed out that the surface brightness profile of the LMC does not allow for a foreground stellar population with a substantial microlensing optical depth to extend beyond 5 degrees from the LMC center. Gould's argument would fail for a foreground population that had a surface brightness distribution so uniform that it could be confused with the sky brightness, however. Johnston has shown theoretically that tidal debris from the LMC or another galaxy would either extend well beyond the LMC or have a very short lifetime unless the associated microlensing optical depth was small. Together the Gould and Johnston arguments show that the scenario in which a foreground of tidal debris accounts for the microlensing seen toward the LMC is rather unlikely. The calculation presented here strengthens their case, and it also applies to objects such as dwarf galaxies that might not extend beyond the foreground of the LMC. Thus, while it is not certain that Zaritsky & Lin's observations really indicate that a foreground stellar population exists, there is now rather strong evidence that such a foreground population of normal stars cannot account for the LMC microlensing events seen by the MACHO Collaboration.

Acknowledgments

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